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CYCLOPS2: the fibre image slicer upgrade for the UCLES high resolution spectrograph

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ABSTRACT

CYCLOPS2 is an upgrade for the UCLES high resolution spectrograph on the Anglo-Australian Telescope, scheduled for commissioning in semester 2012A. By replacing the 5 mirror Coudé train with a Cassegrain mounted fibre-based image slicer CYCLOPS2 simultaneously provides improved throughput, reduced aperture losses and increased spectral resolution. Sixteen optical fibres collect light from a 5.0 arcsecond² area of sky and reformat it into the equivalent of a 0.6 arcsecond wide slit, delivering a spectral resolution of $R = 70000$ and up to twice as much flux as the standard 1 arcsecond slit of the Coudé train. CYCLOPS2 also adds support for simultaneous ThAr wavelength calibration via a dedicated fibre. CYCLOPS2 consists of three main components, the fore-optics unit, fibre bundle and slit unit. The fore optics unit incorporates magnification optics and a lenslet array and is designed to mount to the CURE Cassegrain instrument interface, which provides acquisition, guiding and calibration facilities. The fibre bundle transports the light from the Cassegrain focus to the UCLES spectrograph at Coudé and also includes a fibre mode scrambler. The slit unit consists of the fibre slit and relay optics to project an image of the slit onto the entrance aperture of the UCLES spectrograph. CYCLOPS2 builds on experience with the first generation CYCLOPS fibre system, which we also describe in this paper. We present the science case for an image slicing fibre feed for echelle spectroscopy and describe the design of CYCLOPS and CYCLOPS2.

Keywords: Instrumentation, spectroscopy, image slicer, integral field unit

1. INTRODUCTION

The University College London Echelle Spectrograph (UCLES)¹ is the high optical spectrograph of Anglo-Australian Telescope (AAT). It has been one of the longest serving, most successful and most productive of the AAT's instruments, and remains in demand due to its ability to contribute to a number of important scientific areas such as exoplanetary science, metallicities and abundances, and asteroseismology. By increasing both the overall efficiency and spectral resolution the CYCLOPS2 upgrade will ensure the continuing competitiveness of the UCLES spectrograph in these areas.

1.1 Exoplanetary science

The 763 exoplanets discovered to date (as of April 2012) have resulted in an enormous increase our knowledge about the formation and evolution of planetary systems. They have also necessitated significant re-evaluation of existing planet formation models. These exoplanets have been the largest single catalyst in an explosion of research in the new fields of exoplanetary science and astrobiology over the last decade.

Detection by the Doppler wobble technique has played a dominant role in this exoplanetary explosion. Doppler searches provide accurate estimates of key exoplanet properties; mass (modulo inclination to the line of sight), period, orbital semi-major axis (ie. orbital size) and eccentricity. Doppler searches have discovered 477 of the currently known exoplanets, and been used to study the properties of 701 of the 763 total. In the process they have told us that while exoplanets are not uncommon ($> 7\%$ of stars host giant planets within 5 AU) and that multiple planet systems exist around

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at least 1% of stars, configurations like our own Solar System seem to be rare, with eccentric elliptical orbits (rather than near-circular orbits) being the norm for exoplanets.

These Doppler searches have come from several major groups, one of which is the Anglo-Australian Planet Search (AAPS). They have used UCLES extensively over the last decade and are carrying out a long term survey to search for giant planets around more than 240 nearby Solar-type stars. The AAPS has established itself in a crucial role, demonstrating extremely high long-term precision.^{2,3}

In addition to this long-term precision, experiments carried out in the last few years with dedicated programs targeting even higher precision. These have demonstrated that for bright stars ($V < 6.5$) that have high intrinsic stability exposures of 15–20 minutes on the AAT can deliver velocity precisions at a level that makes the detection of terrestrial-mass planets in short-period orbits feasible.

1.2 Metallicities and abundancies

The ancient star forming events that built up the galactic disk leave traces of their presence many Gyr later. Stellar substructure in the nearby disk provides a way to probe these ancient events. Although some of the dynamical information about these events has been lost, detailed chemical signatures over many chemical elements provide a way to associate or tag nearby stars to common ancient star forming events. UCLES has previously been used for this kind of research using targets identified by the RAVE survey, and in coming years UCLES will complement the GALAH spectroscopic survey undertaken by HERMES multiobject high resolution spectrograph currently under construction for the AAT.⁴ The greater wavelength coverage and higher spectral resolution of UCLES will allow it to perform detailed follow up studies of unusual stars identified by HERMES.

1.3 Asteroseismology

The past few years have seen great progress in measuring oscillations in solar-type stars, thanks to the tremendous velocity precision being developed for hunting planets. UCLES with its iodine cell plays a vital role in measuring stellar oscillations,^{5,6} not least because the longitude of the AAT makes it central to obtaining temporal coverage that is as continuous as possible. Multi-longitude observations reduce the 1/day aliasing that is a big problem for single-site observations.

Measuring stellar oscillations is an elegant physical experiment. A star is a gaseous sphere that oscillates in many different modes when excited. The oscillation frequencies depend on the sound speed inside the star, which in turn depends on properties such as density, temperature and composition. The Sun oscillates in many modes simultaneously and comparing the mode frequencies with theoretical calculations (helioseismology) has led to significant revisions to solar models. The recent revision of solar abundances poses a new challenge in which helioseismology is sure to play an important role.

Measuring oscillation frequencies in other stars (asteroseismology) allows us to probe their interiors in exquisite detail and study phenomena that do not occur in the Sun. We expect asteroseismology to produce major advances in our understanding of stellar structure and evolution, and of the underlying physical processes.

The difficulty in observing solar-like oscillations lies in their tiny amplitudes (less than a metre per second). Thanks to the Doppler precision provided by spectrographs such as UCLES, UVES and HARPS, the field of asteroseismology has finally become a reality.

The University of Sydney asteroseismology group have used UCLES in combination with UVES, HARPS or CORALIE to observe five stars (beta Hyi, alpha Cen A & B, nu Ind, Procyon). However, the data from UCLES are substantially inferior to those from HARPS and UVES because, although the precisions of all three systems are comparable, the seeing induced slit losses at the AAT substantially degrade the signal-to-noise ratio of the spectra. A significant increase in the throughput of UCLES (from CYCLOPS2) would be a tremendous advantage for this work.

2. INSTRUMENT DESIGN

2.1 UCLES

UCLES is cross-dispersed Echelle spectrograph located at the Coudé focus of the 3.9 m Anglo-Australian Telescope (AAT). A variable width slit allows spectral resolutions of up to $R \approx 100000$ to be achieved. To keep slit losses at acceptable levels a slit width of approximately 1 arcsecond is more typical, which results in a spectral resolution of $R \approx 45000$. The instrument resides in an insulated but not actively stabilised spectrograph room. Wavelength calibration is performed using a ThAr hollow cathode arc lamp and an iodine absorption cell is available for precision radial velocity measurements.

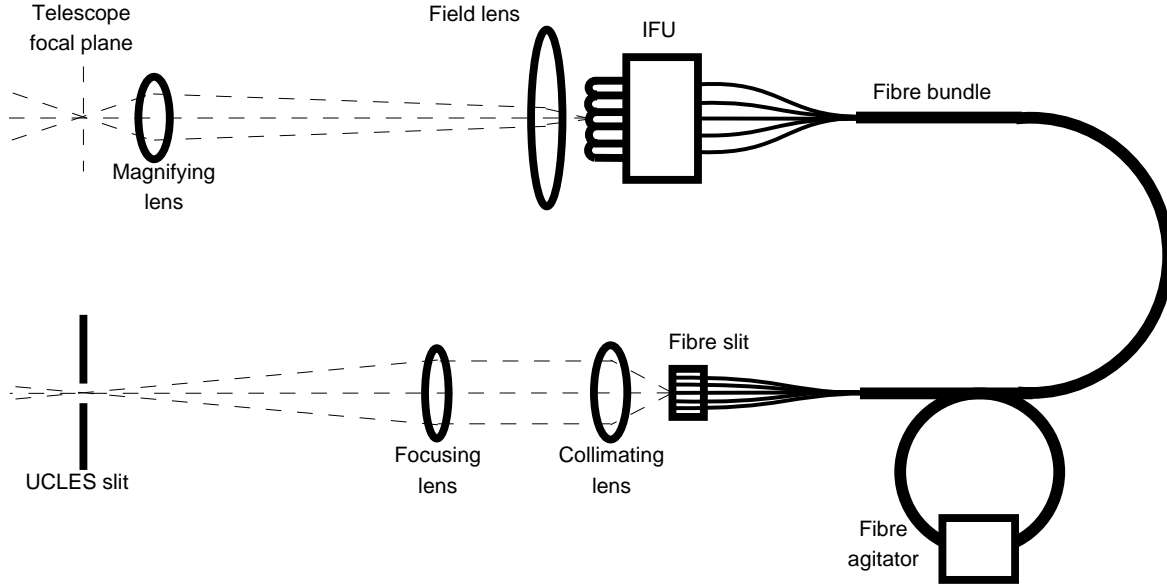


Figure 1. Schematic showing the main elements of the CYCLOPS/CYCLOPS2 fibre feeds. Not shown are the calibration, acquisition and guiding components which differ between CYCLOPS and CYCLOPS2.



Figure 2. Photographs of the CYCLOPS IFU showing the lens array attached to the front surface of the substrate (left) and the array of fibres attached to the rear surface of the substrate (right).

2.2 CYCLOPS

The CYCLOPS fibre feed concept is illustrated schematically in figure 1. It consists of three main components, the fore-optics unit, the fibre bundle and the slit unit.

The fore-optics unit mounts at a Cassegrain focal station of the AAT, and incorporates optics which project a flat, telecentric and magnified sky image onto a lenslet array. The array is assembled from individual hexagonal lenslets 2 mm across (flat to flat) giving a spatial sampling of 0.6 arcseconds. There are 15 lenses in total providing a roughly circular light collecting area of 4.7 arcsecond². The lenslet array projects an image on the telescope pupil onto the core of each of the 15 fibres attached to the rear of the array substrate. To maximise coupling efficiency each fibre was individually aligned with the corresponding lenslet during assembly. Figure 2 shows photographs of the CYCLOPS integral field unit (IFU) assembly (which includes the lenslet array, fibre array and the substrate between them) taken during integration.

The fibre bundle transports the light from the fore optics unit to the UCLES spectrograph at the Coudé focus position, a total distance of approximately 28 m. The fibre used in the current CYCLOPS implementation is Polymicro FBP custom

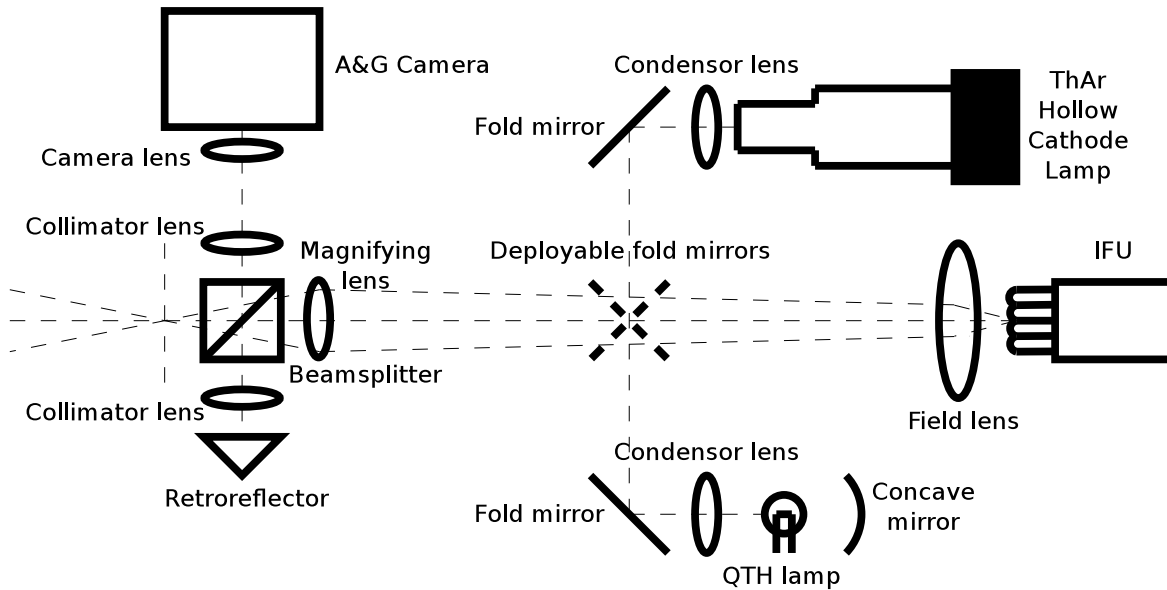


Figure 3. Schematic of the CYCLOPS fore optics unit including the calibration, acquisition and guiding systems. In the CYCLOPS2 implementation these functions are provided instead by the CURE facility.

drawn with 70/84/95 μm core/clad/buffer diameters. The fibres are protected by an armoured limited-bend flexible conduit. The fibre bundle also incorporates a fibre agitator to prevent fibre modal noise degrading the signal-to-noise ratio of the spectrograph.

The slit unit terminates the fibre bundle in a close packed linear array, and includes an optical relay that reimages this fibre pseudo-slit onto the UCLES spectrograph slit. This relay converts the $f/5$ beam exiting the fibres to an $f/36$ beam entering the spectrograph, resulting in an effective slit width of 500 micron and a spectral resolution of 70000. The length of the fibre slit is limited by the inter-order separation of the UCLES spectrograph, the decision to use a close packed fibre slit and thin fibre cladding and buffer layers were made in order to maximise the number of fibres that could fit into the slit.

In addition the CYCLOPS fore optics unit also contains dedicated calibration, acquisition and guiding systems. These were included in CYCLOPS because the existing facilities available at the AAT Cassegrain focal stations did not meet the requirements of CYCLOPS. Figure 3 illustrates these components. A beamsplitter near to the telescope focal plane redirects a few percent of the incoming light to an acquisition and guide camera. When back-illuminated the IFU can also be seen by the acquisition and guide camera, via a retroreflector on the opposite side of the beamsplitter. This is used during initial setup in order to determine the approximate position of the IFU in the camera's field of view prior to fine tuning using stellar images reconstructed from the IFU itself. A quartz tungsten halogen lamp for flat-fielding and a ThAr hollow cathode lamp for wavelength calibration are also included. These illuminate the IFU using fold mirrors which can be deployed into space between the two fore optics lenses.

The CYCLOPS fibre-feed was commissioned during a series of runs in semesters 2010B and 2011B and is now available to the community. See <http://www.phys.unsw.edu.au/~cgt/CYCLOPS/CYCLOPS.html> for further details.

2.3 CYCLOPS2 and CURE

CYCLOPS2 is a second generation fibre feed for UCLES. There are two main reasons for building a second fibre feed. First, difficulties during the assembly of CYCLOPS resulted in 3 of the 15 fibres being damaged and as a result CYCLOPS has only 12 operational fibres. This resulted in higher aperture losses than intended and unfortunately repair of the damaged fibres would not be possible without rebuilding the entire IFU-fibre bundle-fibre slit assembly. The second reason for replacing CYCLOPS was in order for the fibre feed to be compatible with the CURE facility.

CURE is a add-on to the AAT's Cassegrain instrument interface intended to simplify and streamline the implementation of fibre-fed and other compact instrumentation with fields of view up to 3 arcminutes in diameter. It will do this by

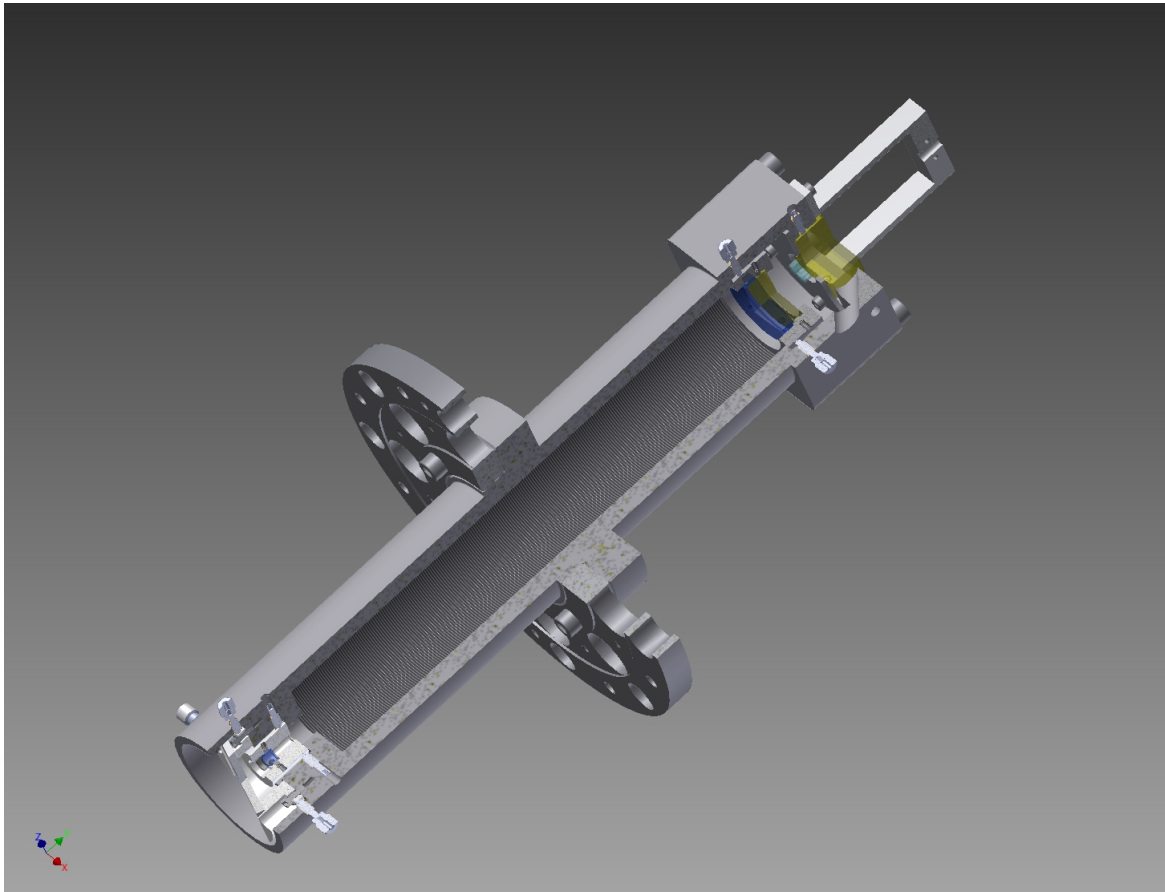


Figure 4. Mechanical model and sectioned view of the CYCLOPS2 fore-optics. From left to right optical elements include a beamsplitter (which is used to direct $\sim 5\%$ of the incoming light to the CURE acquisition and guiding camera), magnifying lens (blue), pupil stop (grey), field lens (blue and yellow), lenslet array (cyan), and substrate (yellow). The fibres are individually bonded to the rear surface of the substrate using a refined version of the techniques initially developed for CYCLOPS. With the exception of the fibre agitator (not shown) CYCLOPS2 is a purely passive opto-mechanical system with no moving parts.

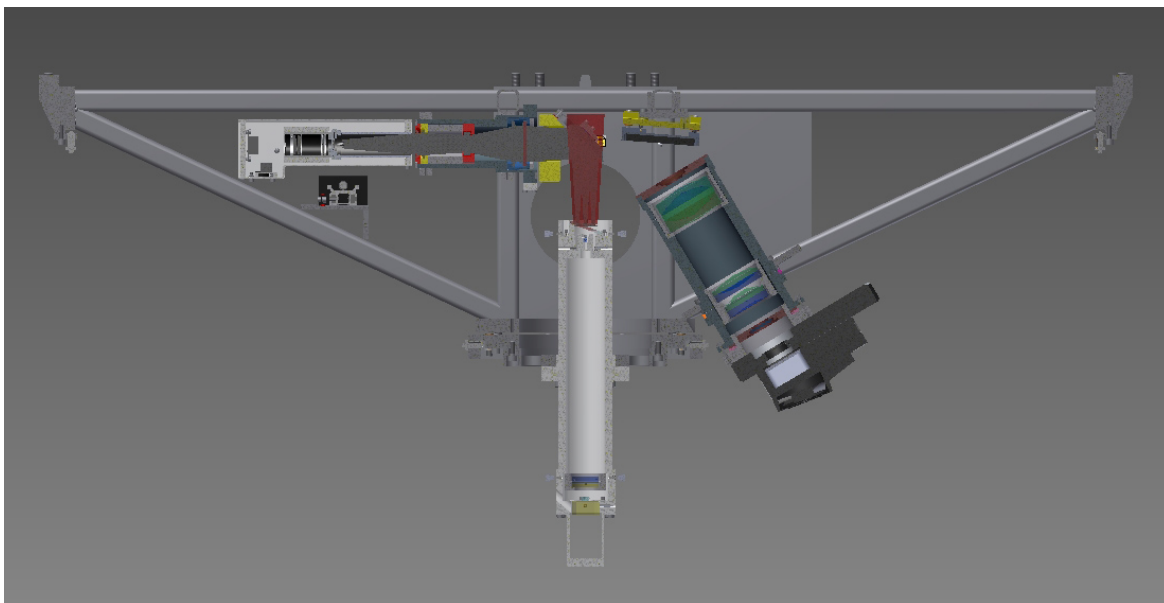


Figure 5. Half-sectioned mechanical model of the CURE facility which mounts to the AAT's main Cassegrain focal station. At the bottom is the CURE instrument interface (shown with the CYCLOPS2 fore optics unit attached), on the right is the acquisition and guiding camera and on the left is the calibration assembly.

providing a suitable standardised mechanical interface as well as improved acquisition, guiding and calibration facilities so that CURE-compatible instruments will not have to incorporate their own acquisition, guiding and calibration systems as CYCLOPS had to. Because of this the CYCLOPS2 fore optics unit is simpler, smaller and more robust than the first generation CYCLOPS unit, the CYCLOPS2 design can be seen in figure 4. The instruments expected to make use of CURE, in addition to CYCLOPS2, are the KOALA IFU for the AAOmega spectrograph,⁷ the PRAXIS OH suppression spectrograph⁸ and a number of visitor and/or experimental instruments. Figure 5 shows the layout of the CURE facility. The instrument interface at the base of CURE is designed to allow easy instrument exchange with repeatable alignment. The acquisition and guide camera looks down on the telescope focal plane via an optical relay and fold mirror, this 'slit viewer' configuration uses either a beamsplitter (as in CYCLOPS2) or a mirrored entrance aperture built into the attached instrument to view the sky. The camera itself is a cooled interline CCD camera equipped with a set of UV, B, V, R, Ic, clear and blank filters, and is suitable for both rapidfire guiding exposures and deep acquisition images. The calibration assembly includes a quartz tungsten halogen lamp for flat fielding and ThAr, CuAr and FeAr hollow cathode lamps for wavelength calibration. The lamps evenly illuminate an area of the telescope plane equivalent to 1.5 arcminutes in diameter on-sky and the relay optics have been designed so that the illumination closely mimics that from the telescope, including the central obstruction of the telescope pupil. Additional calibration options are available using the existing discharge lamps in the AAT's acquisition and guiding unit and chimney.

The decision to replace CYCLOPS also provided an opportunity for upgrades compared to the original specifications. It was determined that by stripping the buffer from the fibres in the fibre slit the fibres could be more closely packed, allowing 16 fibres to fit within the inter-order separation of the UCLES echellogram instead of the original 15. It was also decided to include a 17th fibre for simultaneous wavelength calibration, a capability that CYCLOPS/UCLES did not have before. Illumination of this fibre with a ThXe hollow cathode arc lamp during science exposures will provide simultaneous wavelength calibration at the expense of contaminating two of the science fibres with calibration light, CYCLOPS2 will therefore be able to operate either with 16 science fibres or with 14 science fibres plus simultaneous wavelength calibration. Figure 6 is a micrograph of the CYCLOPS2 fibre slit. The individual fibres have been close packed in direct contact with adjacent fibres and with the precision machined slit blocks on each side with the result that the variation in fibre core positions both along and perpendicular to the slit axis are within $\pm 1 \mu\text{m}$.

At time of writing the CYCLOPS2 fibre-feed and the CURE facility are both in the final integration and assembly phase. A series of commissioning runs at the AAT are scheduled for the second half of 2012.

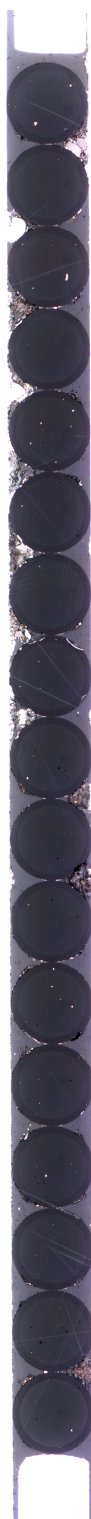


Figure 6. Composite micrograph of the CYCLOPS2 fibre slit.

3. SUMMARY

A fibre image slicer can simultaneously improve the throughput, reduce aperture losses and increase the spectral resolution of a high resolution spectrograph, significantly improving its overall performance. The CYCLOPS2 fibre-feed, an upgrade for the UCLES high resolution spectrograph on the AAT, promises to be a powerful instrument for a range of science cases including Doppler exoplanet searches, stellar chemical abundance studies, and asteroseismology

REFERENCES

- [1] Diego, F. et al, “Final tests and commissioning of the UCL Echelle Spectrograph,” in *Instrumentation in astronomy VII, Proc. SPIE* **1235**, 562–576 (1990).
- [2] Tinney, C. G. et al, “First Results from the AngloAustralian Planet Search: A Brown Dwarf Candidate and a 51 Peglike Planet,” *ApJ* **551**, 507–511 (2001).
- [3] Vogt, S. S. et al, “A super-Earth and two Neptunes orbiting the nearby Sun-like star 61 Virginis,” *ApJ* **708**, 1366–1375 (2010).
- [4] Barden, S. C. et al, “HERMES: revisions in the design for a high-resolution multi-element spectrograph for the AAT,” in *Ground-based and Airborne Instrumentation for Astronomy III, Proc. SPIE* **7735**, 773509–773509–19 (2010).
- [5] Bedding, T. et al “Detection of stellar oscillations with UCLES: the birth of asteroseismology,” *AAO Newsletter* **99**, 12 (2002).
- [6] Bedding, T. et al “Asteroseismology with UCLES,” *AAO Newsletter* **111**, 10 (2007).
- [7] Ellis, S. C. et al, “KOALA: a wide-field, 1000 element integral field unit for the Anglo-Australian Telescope,” in *Ground-based and Airborne Instrumentation for Astronomy IV, Proc. SPIE* **8446**, 84460V–84460V–8 (2012).
- [8] Horton, A. et al, “PRAXIS: a low background NIR spectrograph for fibre Bragg grating OH suppression,” in *Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II, Proc. SPIE* **8450**, 84501V–84501V–6 (2012).